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Generation of Accelerated Electrons in a Gas Diode with Hot Channel

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Abstract—Generation of fast electrons in an inhomogeneous medium composed of a hot channel (spark channel, laser plume, etc.) surrounded by air under normal conditions has been numerically analyzed. The model used makes it possible to carry out consistent calculation of the formation of subnanosecond gas discharge and generation of accelerated electrons under these conditions. The fast-electron current is found to consist of two pulses. One of them has an amplitude of 50 A, width of 30 ps, and electron energy of more than 100 keV. These electrons are generated in the hot channel. The other pulse has an amplitude of 170 A, width of 20 ps, and electron energy in the range of 8–50 keV. These electrons are generated in cold air. Since these pulses pass successively and barely overlap, the total width of fast-electron pulse is almost 50 ps.

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Formation of fast-electron beams in high-pressure gases (in particular, air) is one of the most interesting problems in gas-discharge physics. This technique can be applied to design electron accelerators without a foil separating the vacuum and gas volumes, which is a weak point of accelerators. The main efforts of researchers are aimed at increasing the efficiency of electron transition to the continuous-acceleration mode, which is a necessary condition for generation of high-power beams of fast electrons. This problem can conventionally be solved using specially shaped cathodes [1–4]. In this case, the efficiency of fast-electron generation increases due to the formation of regions of enhanced electric field in a gas-filled diode. However, the efficiency of electron transition to the continuous-acceleration mode is well known to be a function of reduced field strength E/N (E is the electric field strength, and N is the concentration of gas molecules).

It was proposed in [5] to increase the E/N ratio by reducing N rather than increasing E (the latter approach is traditionally used). To this end, a high-temperature discharge region must be formed near the cathode. This may be, for example, a laser plume or a spark channel that stopped expanding thermally and recovered electric strength due to the recombination. When the pressure in this hot channel becomes equal to the environmental one, neutral particles are distributed according to the relation $p_{atm} = NkT$, where p_{atm} is the atmospheric pressure, N is the concentration of neutral particles, k is the Boltzmann constant, and T is temperature. Note that the concentration of neutral particles in the hot channel is inversely proportional to its temperature. For example, since the temperature in a laser plume is close to the boiling temperature of the target material (i.e., several thousands of kelvins) in the mode of developed evaporation [6] and amounts to several tens of thousands of kelvins in the optical-breakdown mode [7], the concentration of neutral particles in the hot channel can be one to two orders of magnitude lower than the concentration of molecules in air at room temperature. Thus, the E/N ratio can be increased by one to two orders of magnitude without increasing E.

The calculations carried out in [5] within the one-dimensional model showed that accelerated electron beams with a current up to 1 kA and a mean energy of about $(2/3)eU$ (U is the accelerating voltage) can be formed. However, the real geometry of a hot channel is disregarded in the one-dimensional model; therefore, these calculations are only estimations and obviously should be refined.

Thus, the purpose of this Letter was to numerically study (within the two-dimensional model) the generation of accelerated electrons under atmospheric pressure in a gas diode with an inhomogeneity (hot channel).

We used the well-known XOOPIC package [8], which was applied previously to simulate the formation of subnanosecond gas discharges and generation of accelerated electrons [9]. This package is based on the method of large particles, which is used to simulate the motion of charged particles in external and inter-

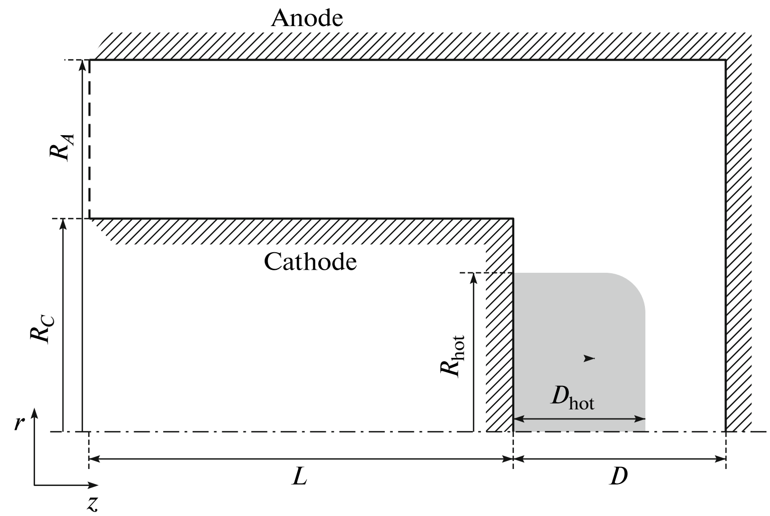

Fig. 1. Geometry of the problem. The hot region is shown in gray. $R_C = 2.5$ mm, $R_A = 7.5$ mm, $R_{hot} = 2.5$ mm, $D_{hot} = 2.5$ mm, $L = 13$ mm, and $D = 7$ mm.

nal electromagnetic fields. Elastic and inelastic electron collisions are simulated by the Monte Carlo method. The dynamics of the electromagnetic field in both the diode and input line is calculated based on the Maxwell equations. The package uses a two-dimensional axisymmetric approximation.

The geometry of the problem is shown in Fig. 1. We simulated a transmitting line with a length $L = 1.3$ cm; a voltage pulse with a front width of 100 ps was fed to one of its ends. A diode with interelectrode distance $D = 7$ mm filled with nitrogen at room temperature and atmospheric pressure was placed at the other end of the line. The transmitting-line length was chosen to be larger than the diode interelectrode distance by a factor of almost 2 to provide a wave propagation time through the line longer than the duration of the processes in the diode we are interested in. As a result, we avoided unnecessary complications related to consideration of wave processes in the line.

The gas region heated to 3000 K was located along the line axis, beginning with the cathode; the numerical density of neutral particles in this region was lower than in the rest of the gap by an order of magnitude. Length D_{hot} and radius R_{hot} of this region (gray in Fig. 1) were 2.5 mm. For simplicity, the electron emission from the cathode was assumed to be free (i.e., the electron work function is zero). This simplification is justified by the fact that, during the formation of a hot region (whether a laser plume or a spark channel), the cathode is intensely heated and has a sufficiently high temperature to emit ensure high thermionic currents.

The calculation results are shown in Figs. 2 and 3. Figure 2 presents calculated ion oscillograms of voltages and total currents (top) and fast-electron currents (bottom). Figure 3 shows the electric-field distribution in the interelectrode gap along the z axis and the phase portraits of electrons at different instants (top).

A distinctive feature of the problem considered here is that the characteristic time for establishing electromagnetic-field distribution in the gap is comparable with the breakdown time. This fact can easily be understood by estimating the electromagnetic wave transit time through the interelectrode gap. It is about 20 ps, i.e., quite comparable with the times in the oscillograms in Fig. 2. Therefore, the voltage across the interelectrode gap can be determined arbitrarily. We defined it as

$$U = \int_0^D E_z(z)dz,$$

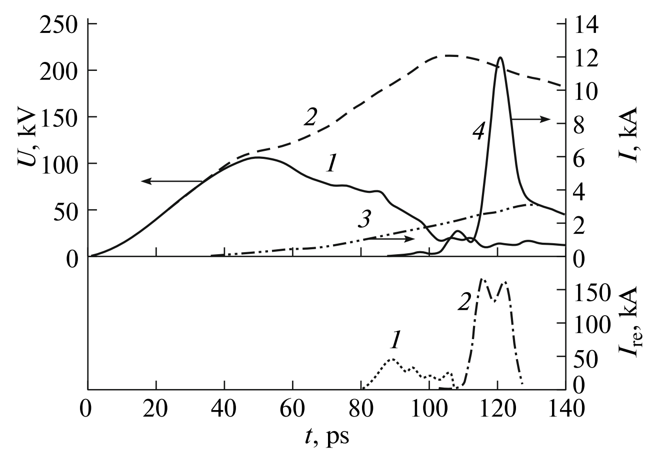

Fig. 2. Calculated oscillograms of voltages and currents in the discharge gap. The upper plot: (*1*) voltage across the discharge gap, (*2*) voltage in the open-circuit mode, (*3*) cathode current, and (*4*) anode current. The lower plot: current pulses of fast electrons with energies (*1*) above 100 keV and (*2*) in the range of 8–50 keV.

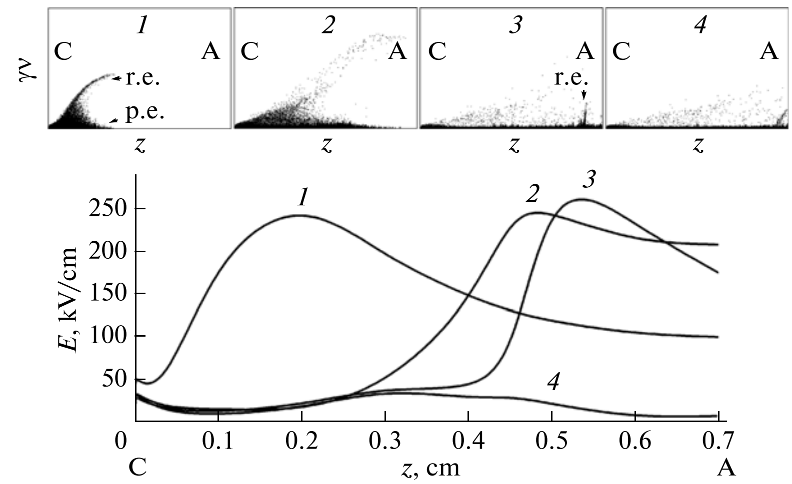

Fig. 3. Distribution of the electric field in the gap at different instants and the corresponding phase portraits of electrons (upper plots). The distribution curves and phase portraits are enumerated identically: (*1*) 40, (*2*) 80, (*3*) 100, and (*4*) 120 ps. The designations are as follows: (C) cathode, (A) anode, (r.e.) runaway electrons, and (p.e.) "slow" plasma electrons.

where D is the interelectrode distance and $E_z(z)$ is the distribution of the z component of electric field strength along the z axis (Fig. 3).

The time dependence of the voltage across the interelectrode gap is shown in Fig. 2 (upper plot, curve *1*). The time dependence of the voltage in the open-circuit mode (curve *2*), i.e., in the absence of gap breakdown, which was obtained by switching off the electron emission from the cathode and ionization processes in the gas medium, is shown for comparison. It can be seen that the voltage across the gap begins to decrease at about 50 ps, the instant when the current from the cathode begins to increase (curve *3*). In this stage, the cathode current is due to the formation of a conducting channel and, accordingly, the change in the diode resistance. In this case, there is an excess negative charge at the channel front, which distorts the electric field in the gap (Fig. 3). When the conducting channel reaches the anode, this excess charge rapidly passes to the anode; as a result, there is a sharp peak of anode current at about 120 ps. When the conducting channel completely covers the gap, the cathode and anode currents become equal.

Figure 2 (bottom) shows the time dependences (calculated oscillograms) of the fast-electron current. This current is a combination of two pulses, which are formed by electrons with different energies. The first pulse (curve *1*) has an amplitude of ~50 A and a width of almost 30 ps. It is formed by electrons with energy of more than 100 keV. The second pulse (curve *2*) is formed by electrons with energies in the range from 8 to 50 keV. It has a somewhat smaller width (17 ps), but a much larger amplitude (170 A).

This behavior of the fast-electron current can be explained as follows: during breakdown development (i.e., while the conducting channel approaches the cathode), fast electrons are generated twice, in different regions of the interelectrode gap.

This process is depicted in Fig. 3. Electrons begin to pass to the runaway mode in the hot region at the instant of about 20 ps. The formed beam of runaway electrons can be seen at the peak of voltage pulse (40 ps) in phase portrait *1*. Here, the field strength in the hot region (curve *1*) is maximal, due to which fast-electron generation becomes more efficient. This beam reaches the anode by the time of 80 ps, acquiring energy comparable with the voltage-pulse amplitude (i.e., above 100 keV). The fast increase in the hot-channel conductivity reduces the electric-field strength of the channel; as a result, the formation efficiency of the fast-electron beam decreases (Fig. 3, curve *2*, phase portrait *2*). This first pulse of the fast-electron current ionizes the gas medium in the direction toward the anode, forming a large number of "seed" electrons therein. The region (cold) before the anode is exposed to a rather strong electric field (Fig. 3, curves *2*, *3*). Intense ionization and transition of some electrons to the runaway mode occur in this field (phase portrait *3*), due to which the second pulse of fast-electron current is formed. Here, the efficiency of transition to the runaway mode is much lower than in the hot region; however, the total current of the second pulse is rather high due to the much higher concentration of plasma electrons. The second pulse of the fast-electron current arrives at the anode by the time of 120 ps (phase portrait *4*). The formation of the conducting channel, which closes the gap, is finished practically are the same instant. As a result, the excess charge leaks to the anode to form the above-considered anode-current pulse. The voltage decreases even more, and the distribution of electric-field strength in the gap can be described by curve *4*.

Since the second pulse of fast-electron current is formed near the anode, do not have electrons enough time for significant acceleration; therefore, their energy does not exceed 50 keV.

Comparison of the results of this study and the 1D-simulation data of [5] revealed significant differences. First, only one (specifically, the first) pulse of the current of fast electrons that passed to the runaway mode in the hot region was observed in [5]. Our calculations yielded two pulses of fast electrons, which were generated in the hot region before the cathode (the first pulse) and in the cold region before the plasma-channel front near the anode (the second pulse). Second, the pulse of the fast-electron current in [5] had much larger amplitude and width. These differences are due to the fact that the volume of the heated region in our study was smaller than that in [5] and the voltage across the gap decreased more rapidly. The more rapid voltage drop across the gap is due to the faster increase in the gap conductivity as a result of more accurate calculation of the dynamics of plasma-channel formation within the 2D approximation; this accuracy cannot be obtained in the 1D model [5]. In addition, the more accurate calculations of the plasma-channel dynamics revealed the second pulse of the fast-electron current before the anode, which could not be observed within the model [5] as well.

Concerning the probabilities of electron transition to the runaway mode, our results and the data of [5] are in good agreement.

Thus, we carried out two-dimensional numerical simulation of the breakdown development in an atmospheric-pressure gas diode with a hot channel by the PIC/MC method.

The calculations revealed a characteristic feature: the presence of two pulses of the fast-electron current formed during breakdown development in different regions of the gas diode. The first pulse is formed in the hot region and has an amplitude of 50 A and a width of 30 ps. The energy of electrons therein exceeds 100 keV (i.e., is comparable with the voltage-pulse amplitude). The second pulse is formed in cold gas before the front of the growing plasma channel near the anode immediately before the closing stage. This pulse has an amplitude of 170 A and a width of 20 ps. The electron energy in this pulse ranged from 8 to 50 keV, i.e., much below the voltage across the gap.

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